NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

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PRESSURIZED SUBMARINE RESCUE

by

R. G. Eckenhoff

Naval Medical Research and Development Command
Research Work Unit M009901A.0006

Released by:

W. C. Milroy, CAPT, MC, USN
Commanding Officer
Naval Submarine Medical Research Laboratory

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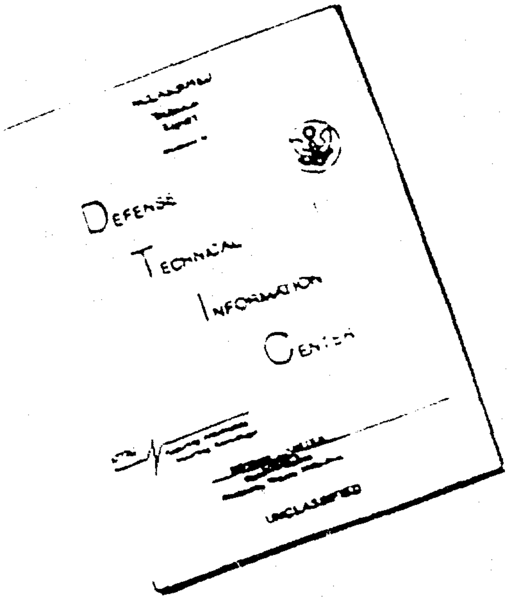

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SUMMARY PAGE

THE PROBLEM:

Disabled submarines are expected to have an elevated atmospheric pressure, and submarine rescue hardware has, in general, been designed to accomplish a rescue under these conditions. However, rescue system hardware deficiencies still exist which could make the logistics of a pressurized rescue difficult. This is certainly due to pressurized rescue being an unauthorized procedure at present, presumably due to the lack of necessary information for dealing with the associated medical problems. Potential medical problems associated with pressurization of a disabled submarine include decompression sickness and pulmonary oxygen toxicity. Decompression schemes for air or nitrox saturation, especially designed for rescue system hardware, are not available. The character or progression of pulmonary oxygen toxicity in hyperbaric air has not been described. This information is necessary to reduce the morbidity and mortality associated with a submarine sinking/rescue.

FINDINGS:

Decompression schemes, including transfer procedures for DSRV to ASR and DSRV to MOSUB and ascent rates for air and nitrox saturation exposures have been formulated and verified with human subjects in a laboratory setting. The onset, character and progression of pulmonary oxygen toxicity in hyperbaric air has been described in human subjects, and recovery in an elevated oxygen environment has been shown. A recent DSRV exercise has shown that serious deficiencies in the pressurization capability exist, which could preclude a successful pressurized submarine rescue.

APPLICATION:

Sufficient physiologic information now exists to allow the authorization of pressurized rescue, and the writing of detailed protocols for the handling of survivors in such a rescue. This will permit appropriate training exercises, with the potential of identifying further procedural and hardware problems which, when corrected, would improve the capability of present submarine rescue systems to perform their primary mission under a variety of circumstances.

ADMINISTRATIVE INFORMATION

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ABSTRACT

Any event that sinks a submarine is likely to cause compression of the atmosphere because of flooding, salvage air pressurization, high pressure air leaks, and exhaust from the open circuit emergency breathing system. The anticipated degree of pressure is impossible to define, but rescue systems (Deep Submergence Rescue Vehicle - DSRV) are limited to a maximum of 5 atmospheres absolute (ATA). The disabled submarine's crew is likely to be exposed for longer than 48 hours. Pressurization significantly complicates the rescue process, since means of pressure equalization and pressurized transfer are required. Medical problems associated with pressurization of the submarine's atmosphere include decompression sickness and toxicity of the inspired gases. Decompression schemes must consider the hardware and procedural constraints involved in submarine rescue. For example, the optimal decompression profile is substantially different depending on whether the DSRV is discharging the survivors to a surface craft (ASR) or another submarine (MOSUB). Decompression schemes, transfer procedures and ascent rates for air or nitrogen-oxygen (nitrox) saturation exposures have been formulated and verified in the laboratory, and are presented in this report. Oxygen toxicity is a potential complication if the pressure is greater than 26 psig due to the elevated partial pressure of oxygen in hyperbaric air. Data is presented, which describes the onset, character and progression of pulmonary oxygen toxicity in hyperbaric air. The toxicity of other atmospheric gases is discussed as well. Pressurized submarine rescue is currently an unauthorized procedure due to the lack of medical knowledge in this area. This report suggests that sufficient physiologic information now exists to allow the authorization of pressurized rescue so that appropriate training exercises can occur. This has the potential of identifying further procedural and hardware problems which, when corrected, would improve the capability of present submarine rescue systems to perform their primary mission under a variety of circumstances.

TABLE OF CONTENTS

I. INTRODUCTION

The current USN submarine sinking record would suggest that a large commitment of resources to provide for submarine rescue in all conceivable situations is unwarranted. Certainly, the last two USN submarines to sink were 20 and 15 years ago, and even the most advanced technology could not have effected rescue because of hull destruction before reaching the bottom. Submarines are not infallible, however, and potentially serious events continue to occur with worrisome frequency.

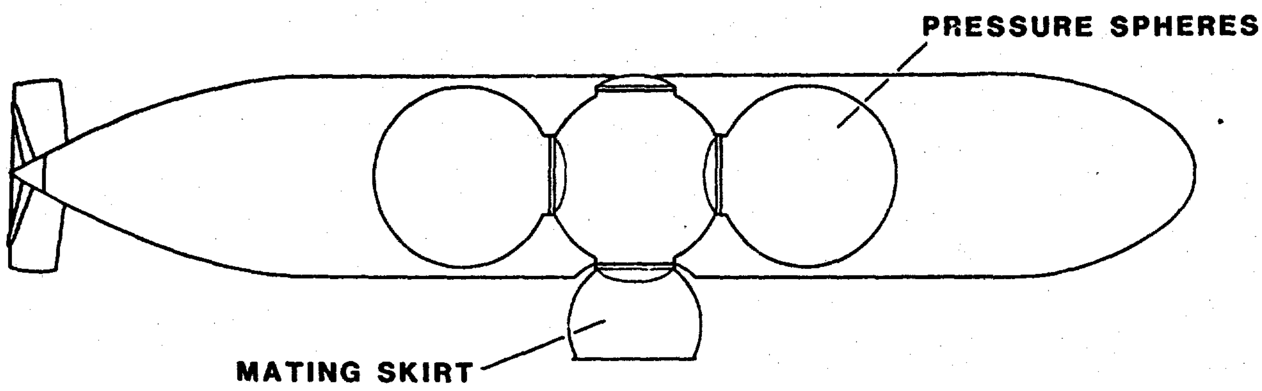
Although the major portion of US submarine operating time is in water deeper than the hull design depth, the relative risk of an incident remains higher over the continental shelf due to heavy sea traffic, danger while surfacing or diving, or undergoing sea trials. Therefore, a submarine sinking with rescuable conditions remains a distinct possibility. To have an intact, but powerless sunken submarine, with a living crew, and inadequate means by which to effect rescue, is entirely unsatisfactory in peacetime. It should be readily apparent that cost/benefit analyses has little relevance in such situations, as the value of 150 highly trained submariners is difficult to assess, as is the impact on the morale of all submarine crews and their families. Therefore, it is vital that a viable capability for the rescue of crews from distressed submarines be maintained, and be sufficiently flexible for a reasonable variety of anticipated complications. This report summarizes current thought and knowledge about the management of one such complication in submarine rescue - that of the internally pressurized distressed submarine (1).

II. THE SYSTEM

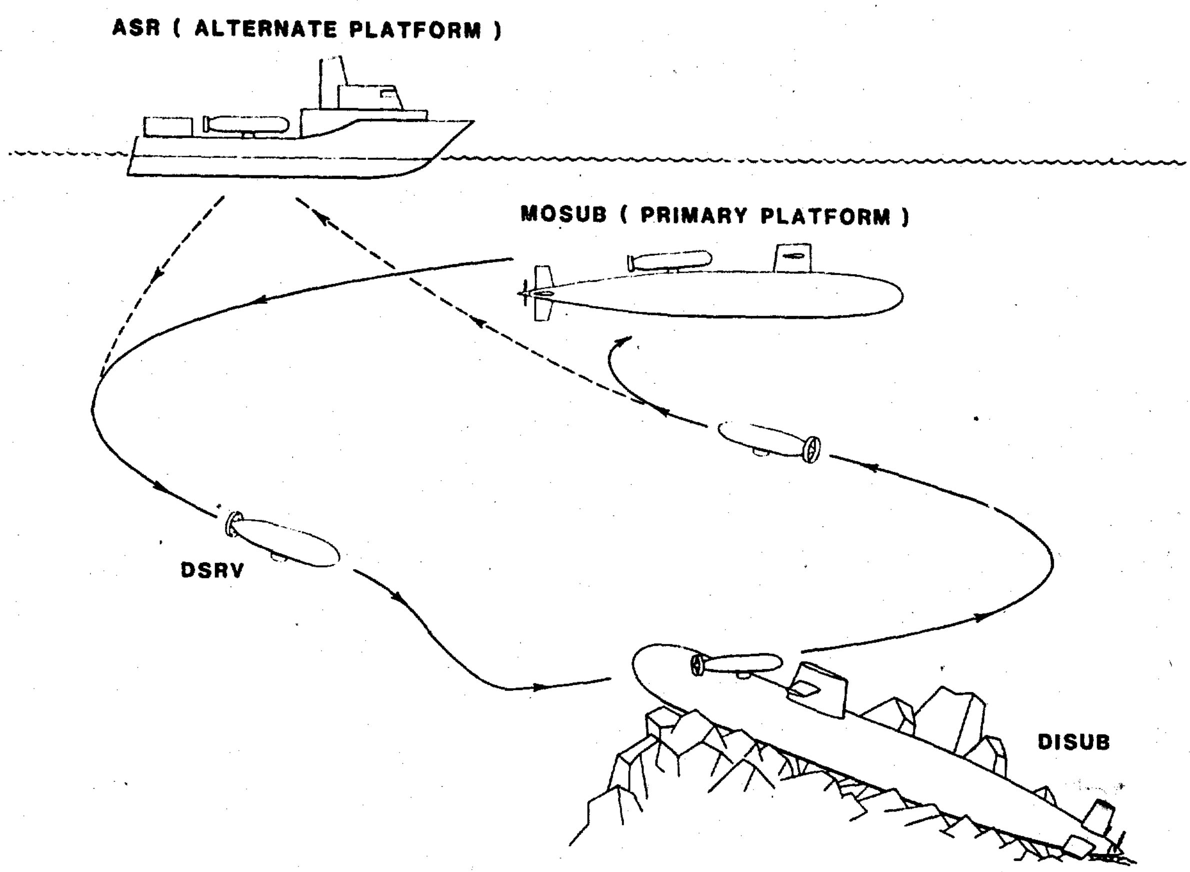
As an aid to understanding the subsequent discussion, this section will describe and review submarine rescue as it is currently envisaged. The sunken distressed submarine (DISUB) sends a distress signal, or misses a routine transmission, and the process begins. Clearly, the time required for this initial step is highly variable, ranging from minutes to days. Although the commanding officer may elect to use individual escape procedures, rescue by submersible is considered the primary or "ultimate" mode of salvaging human life. The principle rescue system currently is the Deep Submergence Rescue System which incorporates the Deep Submergence Rescue Vehicle (DSRV). The DSRV is a small submersible (shown schematically in Fig.1) which can be transported to the scene by land, sea, air or any combination thereof. Although it is an untethered submersible, it cannot operate entirely independently. It must operate from either a surface ship, such as a submarine rescue craft (ASR) or attached in 'piggyback' fashion to a specially modified submarine, called a mother submarine (MOSUB). The 637 class of US nuclear submarine has been modified to serve as MOSUBs (19 submarines)(2). A schematic diagram of a "typical" rescue mission is shown in Fig.2.

The DSRV would arrive on scene attached to MOSUB or carried on ASR, and would then disembark and travel on its own power (electrical), completely

DSRV



1. Schematic diagram of the Deep Submergence Rescue Vehicle (DSRV), showing the three connected pressure spheres. Two operators stay in the forward sphere, and the survivors plus two tenders are in the two aft spheres. The mating skirt connects to the mid sphere through an outward opening hatch.



2. "Typical" rescue scenario. The DSRV operates from either a surface craft (ASR) or a mother submarine (MOSUB) and travels under its own power to the disabled submarine (DISUB). Several Trips may be required as the DSRV holds only 24 survivors. The DSRV must perform a "mate" to the MOSUB, whereas it is actually lifted clear of the water on the ASR (Pigeon class).

untethered. It finds the DISUB by sonar, and can remember its footsteps via an inertial guidance system, or a DSRV-placed transponder - to speed and simplify subsequent trips. Around the DSRV lower hatch is a mating skirt, which is designed to seal over either the forward or after DISUB escape hatch. Water is then removed from the mating skirt, and replaced with air at 1 atmosphere absolute pressure (ATA). It is important to note that no lock or holding device secures the DSRV to the DISUB. They are held together by differential pressure across the mating skirt (2700 in^2 sealing area). Because of this, a minimum depth of 200 feet sea water (90 psi or about 240,000 lbs of sealing pressure) is required to firmly hold DSRV to DISUB; i.e., rescue by DSRV cannot safely occur in water less than 200 fswg.

If the DISUB does lie at depths of less than about 200 fsw, and if the decision to await rescue is made over individual escape, then a different submersible must be used. In this case, the logical choice would be the McCann Submarine Rescue Chamber (SRC), which was used for the successful rescue of crew members of the USS Squalus in 1939. The SRC uses locking devices other than differential pressure for a secure mate, and therefore could be used for shallow rescue.

Once the interior of the DSRV mating skirt is dry, hatches of both the DSRV and DISUB can be opened. Before this, however, the DISUB atmosphere should be sampled for contamination, pressure or radioactivity. This can be accomplished by explosively driving a hollow stud/valve through the DISUB hatch. If the DISUB atmosphere is determined to be safe, the hatch would then be opened, and personnel/supply transfers would occur. To disembark, the DSRV crew would then reverse procedures and travel back to either MOSUB or ASR where transfers again would occur. In contrast to the DSRV-DISUB mate, the DSRV is firmly locked onto the aft escape hatch of MOSUB by hydraulic latches, so it can safely mate shallower than 200 fswg. The DSRV could also mate to forward escape hatch of MOSUB to discharge the survivors into the compressible (see below) forward compartment, but battery power may not be sufficient to make yet another mate to the aft hatch for recharging (hook-ups only available at aft hatch). Once mated to MOSUB, the skirt is again dewatered, hatches opened and personnel transferred. After offloading, DSRV supplies are replenished, batteries recharged (about 12 hours) and it returns to DISUB for another load. DSRV normally carries 4 crew (2 operators in forward sphere, and 2 attendants in mid and aft spheres). It can carry up to 24 passengers; several trips would be required as the average submarine complement is about 130 men. Turnaround time for each trip is limited primarily by battery charging. However, if the DSRV is operating from an ASR, the battery can be <u>changed</u> and thus reduce turnaround time.

III. CAUSES OF DISUB PRESSURIZATION

Any event that sinks a submarine has a high probability of causing pressurization of the submarine atmosphere above the normal 1 ATA. Causes, in a probable order of importance include:

Flooding. Any water entry in a closed system will increase the atmospheric pressure. If half of the submarine floods, the pressure increases to 2 ATA and so forth.

Salvage air pressurization. An option available to the submarine commanding officer, should water entry or compartment integrity be a concern, is to pressurize the compartment(s) with the compressed air supply. This may help to hold water out, or bolster marginal compartment walls against the ambient sea water pressure. Depending on depth, this may also help to empty flooded compartments to give sufficient buoyancy to float the DISUB. However, disaster protocols call for this procedure only if the submarine is at or near the surface.

High pressure air leaks. Any structural damage resulting from collision or explosions may rupture the abundant high pressure gas lines in the DISUB. This may increase the pressure in the submarine by dumping the contents of high pressure gas flasks directly into the submarine's interior.

Built in Breathing System (BIBS) exhaust. Disaster protocols call for the crew to don the emergency breathing devices (BIBS), which are open circuit demand regulators attached to the submarine's high pressure air system. The exhaled gas exhausts directly to the atmosphere, thus increasing the pressure. This source will increase the pressure gradually, while the above three will cause a rapid, sustained pressure increase.

In considering the likelihood of pressurization in a DISUB, it should be realized that few events other than collision and uncontrolled flooding can cause a submarine to sink. Also, salvage air pressurization may be used in an attempt to reduce flooding, the initial trauma may have caused high pressure air leaks, and the BIBS will likely be employed because of atmosphere contamination. Therefore, all of the above factors may coexist. Thus, although this discussion remains largely speculative, it seems inconceivable that a submarine could sink without some elevation of its internal pressure.

A reliable means of reducing the DISUB's internal pressure, once it is on the bottom, is not available. Presumably, some sort of manual device could be installed to pump the air against a pressure gradient to the seawater, but this may be counterproductive as it is also removing an important source of oxygen, and the crew may not yet know of their rescue status. Alternatively, hoses could be attached to external connections on the DISUB by rescue divers or submersibles which could be used to control both pressure and atmosphere. This concept is being investigated by the French Navy, but certain procedural problems must be solved before it can be considered a viable solution to the problem of DISUB pressurization. These problems include stable positioning of the surface vessel tending the hoses, and the means of attaching the hoses to the DISUB.

IV. DEGREE OF PRESSURIZATION

Since no precedents are available, prediction of the degree of DISUB pressurization must also rely upon speculation. Clearly, it could range from 1 ATA to ambient sea water pressure. However, it is important to recognize that early action may limit the degree of pressurization to something less than ambient if flooding is the primary problem. To design a rescue system capable of effecting a rescue over such a wide range of pressures (theoretically from 1 ATA to hull limit) is unreasonable, as large degrees of pressure would presumably indicate significant flooding, and the crew's demise (due to hypothermia or atmosphere toxicity) would occur long before any rescue system could arrive. For these reasons, the DSRV was designed to attain an internal pressure of up to only 5 ATA. Therefore, the range of pressures in the DISUB to be concerned with has narrowed to between 1 and 5 ATA, and the remainder of this discussion will be limited to this range. This still represents a wide range in terms of human tolerance, but to narrow it further is essentially impossible. The number of variables involved make possible an almost infinite number of scenarios. Further, prediction of the most likely scenario is difficult because of the very nature of the event, i.e.; an accident[1]. Ultimately, procedures covering the entire capability of the DSRV (1-5 ATA) are required.

(footnote 1: An accident is defined as an event occurring by <u>chance</u> or arising from <u>unknown</u> causes.)

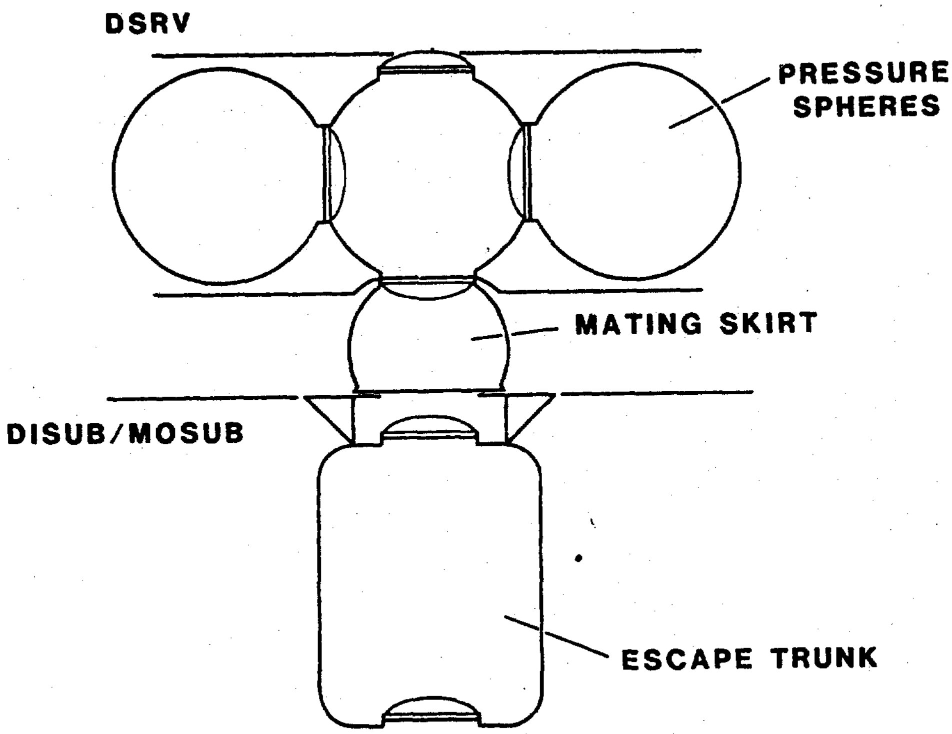
V. PROBLEMS RESULTING FROM PRESSURIZATION

The problems resulting from increased pressure inside the DISUB simplify to three categories: mechanical, decompression obligation and toxicity of respired gases. Each will be discussed in detail.

A. Mechanical

Pressurization of the DISUB creates several uniquely mechanical problems (refer to Fig. 3 for a diagram of the hatching arrangement of a mated DSRV). Since it is essentially impossible to open a hatch with a large differential pressure across it, some means of pressurizing the DSRV/mating skirt must be available for equalization to occur, thereby permitting the DISUB hatch to be opened. First, however, the pressure inside of DISUB must be known. If communication is established, the DISUB crew can relay this information, but if not avaliable, the pressure must be measured by the DISUB crew as described in the section on THE SYSTEM (explosive stud gun). In either event, it is important that the DSRV gauges are accurate and are calibrated in the same units of pressure as the DISUB (psi in US and bar (~ATA) in UK submarines).

Normally, only the mid and aft spheres of DSRV are pressurized,; the forward (operators) sphere would be isolated by closing a pressure tight hatch. At present, the DSRV pressurization system consists of several small compressed air flasks inside the DSRV hull, which are opened directly to the DSRV interior. The routinely available supply will allow pressurization to about 1.8 ATA instead of the desired 5 ATA (3). Since the two spheres to



3. Hatching arrangement of mated DSRV. Note particularly the direction of hatch opening, and the four compartments requiring pressure equalization - DSRV interior, DSRV mating skirt, submarine escape trunk, and the submarine itself (either DISUB or MOSUB).

be compressed have a floodable volume of about 175 ft^3 each, then about 1400 ft^3 of air, compressed into cylinders, must be carried. Unfortunately, this represents a large number of extra cylinders (about 20 standard SCUBA bottles). An external bank of cylinders, valved into the DSRV, would be preferable to trying to decide how many bottles to carry prior to knowing the DISUB internal pressure. Alternatively, after the air in the DISUB is verified to be safe, the DSRV could be slowly pressurized by the DISUB's atmosphere through the stud/valve driven into the DISUB hatch. The same concept could be accomplished by "cracking" the DISUB hatch (since it opens outward) instead of using the hollow stud, but this method would be less controllable, and may result in losing a mating skirt seal. These latter procedures have the advantage of equalizing pressure without depending on gauges, as well as slightly lowering the DISUB pressure with each run, but the DISUB pressure must still be known, so as not to exceed DSRV capability.

Once the DISUB internal pressure is known (after the first trip), the DSRV could be <u>pre-pressurized</u> just before disembarking from a MOSUB. This would occur by pressurizing the entire escape trunk/mating skirt/DSRV complex using MOSUB compressed air, sealing the DSRV, and then disembarking in the usual way. This would be impossible if the DSRV is operating from an ASR, as no mating surface for the skirt is available. Neither does a pressurization connection exist in the DSRV. This 'priming' concept would appear to have some utility if several trips are required, but it would dramatically increase the decompression obligation of the tenders (see below), and therefore complicate subsequent handling.

Once pressurization is complete, hatches opened and the survivors transferred, the procedure is reversed and DSRV returns to either MOSUB or ASR. The DSRV has no valve by which to de-pressurize (decompress) itself. This can only be accomplished in two ways, depending on whether an ASR or MOSUB is the support craft. If a MOSUB is used, the DSRV seats itself to either forward or aft (usually aft because of the cradling supports and locking mechanism) escape hatches, seals and de-waters in the usual manner. MOSUB would then open the escape hatch, and pressurize the escape trunk/mating skirt complex to equal the pressure in the DSRV. The DSRV hatch could then be opened, and the entire escape trunk/mating skirt/DSRV complex decompressed via the escape trunk vent and drain valves. Should the pressure be of sufficient magnitude as to require prolonged decompression (see below), the forward compartment of MOSUB would be preferable, since it could serve as a recompression chamber. The forward compartment of US MOSUB has been designed and fitted to be pressurized to 4 ATA (2), using MOSUB's own compressed air supply. In practice, this is very difficult because of the pressure-sensitive equipment stored in the forward compartment, and the limited access after pressurization. Food, clothing, bedding, medical supplies, atmosphere monitoring and control equipment and trained personnel would all be required in this compartment if it were to be used for decompression of survivors, and would have to placed there prior to pressurization. Replenishment of these items would probably require the MOSUB to come to the surface, to access the escape hatch. The actual decompression strategy, ascent rates, intervals, etc., will be addressed in a subsequent section.

If an ASR is used for support, the DSRV must be decompressed in a potentially hazardous manner. In this situation, the only means by which DSRV can decompress is to very slowly release the dogs (bolts) that hold the outward opening hatch closed. Although this has been demonstrated to be feasible from pressures of less than 1.5 ATA, it is possible that these dogs will be immovable when there is 4 ATA of differential pressure across it, as this represents over 14 tons of pressure (25" hatch diameter) on bolt contact points. Additionally, ascent rates may be difficult to control with this method of decompression. A means of sealing the mating skirt to the top hatch (PTC hatch) of the deck decompression chamber (DDC) on the ASR would be vastly superior, as the chamber decompression system could then be used to control ascent rates, or allow transfer of survivors into the DDC for storage and decompression. Such a mating adaptor has been designed, but never fabricated.

B. Decompression obligation.

Any acute exposure to elevated atmospheric pressure will result in the uptake of inert gas (in the case of air - nitrogen) by the exposed organism (in this case - a submariner). Should this proceed beyond a specific point, the submariner can only be gradually returned to normal pressures, so that the dissolved inert gas can be eliminated while still dissolved. If de-pressurization (decompression or ascent) is too rapid, the inert gas cannot remain dissolved (supersaturation), and will form a gas phase (bubbles) prior to elimination from the body. These bubbles, through a variety of complex mechanisms, may then go on to produce the decompression sickness syndromes. This is a gross oversimplification of the process, but it is not the purpose of this report to review the pathophysiology of decompression sickness; adequate reviews are contained in the literature (4).

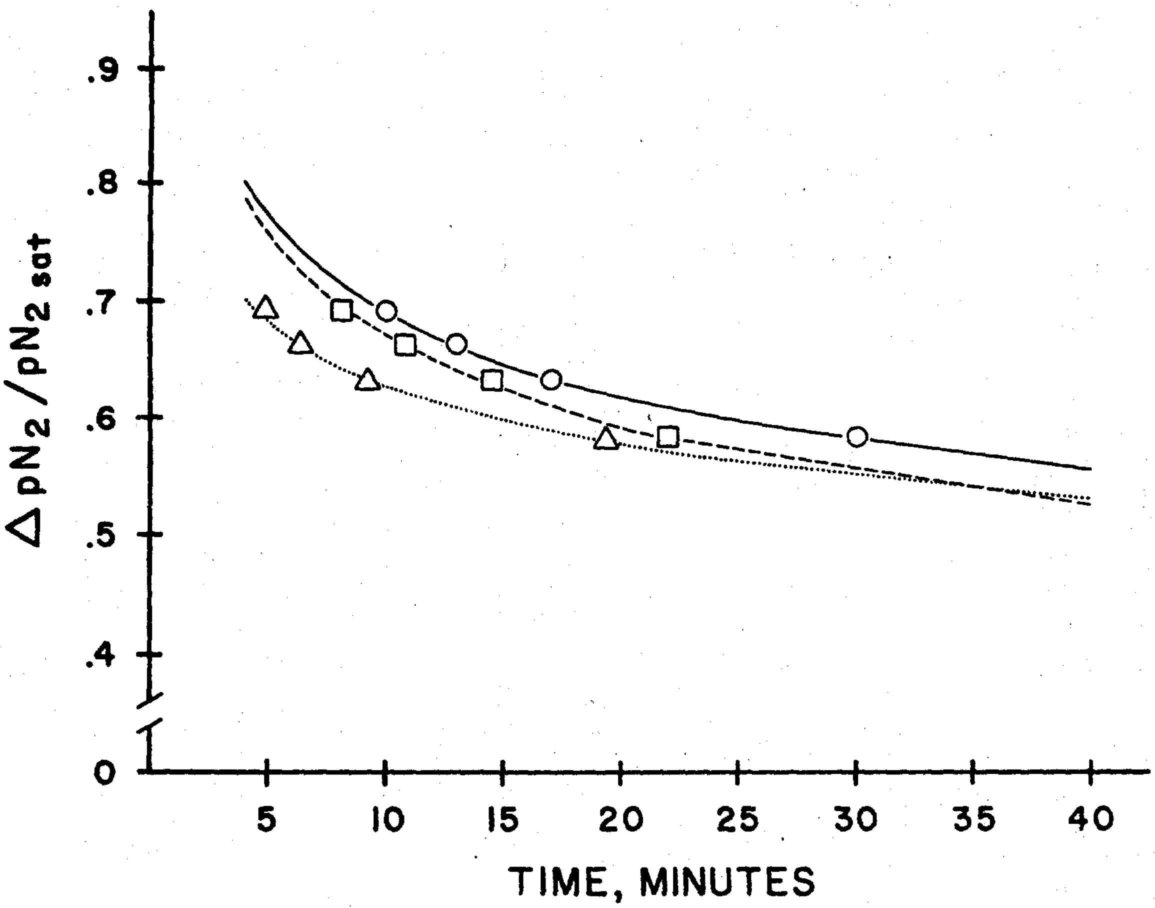
It was established above that the DISUB crew will be exposed to pressure for prolonged periods of time, probably longer than 48 hours. This amount of time will result in complete "saturation" of the body at the new inert gas partial pressure. Some tissues eliminate the inert gas very slowly, and these "slow" tissues will control the ascent rates. Therefore, a long period of time (in excess of 20 hours for even shallow exposures) is required for decompression from saturation dives. Although official decompression schedules for saturation on other gas mixtures (helium-oxygen) have been established, no proven schedules for air saturation exist. Furthermore, the transfer procedures between DSRV and MOSUB or ASR become complicated; the capabilities of the receiving vehicle are very important. To discuss this area adequately, the remainder of this section will be divided into two categories; a) transfer procedures and b) decompression schedules.

1. Transfer procedures.

Transfer of the occupants of the pressurized DSRV to a pressurized chamber is necessary for safe decompression of the survivors as well as to enable DSRV to return to DISUB for another load of survivors. The necessary transfers have been mentioned above. Briefly, two kinds are involved: DSRV to ASR and DSRV to MOSUB (transfer from DISUB to DSRV has already been discussed). The optimal type of decompression will depend largely on hardware and procedural considerations.

DSRV to ASR. As stated above, a pressurized transfer of DSRV personnel to the DDC on the ASR is currently impossible since the mating adaptor has not been fabricated. Therefore, transfer must involve a short interval on the surface (1 ATA), during which the survivors are hurried from the DSRV to the DDC, where they would be re-compressed. Evidence from short hyperbaric exposures would suggest that the latent period for decompression sickness is sufficiently long that this concept (surface decompression - "sur-d", "decanting") may be valid.

Recent studies at this laboratory have demonstrated the feasibility of this approach, within limits, from saturation exposures as well. In these experiments (SUREX), the time to doppler detected pre-cordial bubbles and DCS symptoms was measured after direct ascent to the surface from saturation at 45, 55, 65 and 75 fswg in 24 human subjects (5). It was found that the relationship between both bubble or symptom latency and pressure drop (drop in PN_2 divided by saturation PN_2) could be described by a simple mathematical function as shown in Fig. 4 and Table 1. This relationship allows prediction of safe surface times based on the anticipated magnitude of the pressure drop. Therefore, a majority of survivors would safely tolerate a surface interval of 13 minutes after direct ascent from 65 fswg. Two factors are important to remember when considering these results. First, the surface interval in the figure and table shown here include the time required for ascent, and the experiments were conducted with an ascent rate of 30 feet/min. Slower ascents will use up valuable surface time, and ascents faster than 60 feet/min. may produce symptoms of pulmonary barotrauma. The inability of the DSRV system to control ascent rate in this setting dramatically reduces the usefulness of this surface decompression (decanting) procedure. Second, the safety of this procedure is relative.



4. The latency of decompression sickness is illustrated by this figure, derived from SUREX data. Mean times of appearance for pruritus (triangles) and VGE (squares) are plotted versus the delta PN_2/PN_{2sat} for the ascending excursion in question. The full excursion durations are plotted as well (circles), and are believed to represent the threshold time for DCS symptoms, not mean appearance time. Using least squares regression analysis, data are fitted to a simple power function, as given in Table 1. Also given in this table are the curve variables, correlation coefficients and levels of significance.

The acceptable type and incidence of DCS will change depending on the prevailing circumstances, and the interval may have to be longer than this research would specify as safe. The effect of extending these surface intervals is not known. It seems likely that an increasing incidence of mild symptoms (type I) would emerge, which would probably be acceptable given the grave circumstances. At least two studies, however, suggest that the more serious decompression symptoms (type II) will be observed (6,7), which would significantly complicate the rescue process, and undoubtedly increase the overall mortality.

TABLE 1

Optimal relationship for delta PN_2/PN_{2sat} versus DCS threshold time and onset times for VGE and pruritus

$$Y = AX^B$$

X	A	B	N	R*	P**
Threshold time for DCS	0.99	-0.16	4	0.999	.001
Onset time for VGE	1.00	-0.18	4	0.998	<.01
Onset time for pruritus	0.83	-0.12	4	0.997	<.01

* correlation coefficient
** df = 2

It has been estimated that at least 15 minutes are required to transfer a full compliment of DSRV personnel to a DDC, and begin recompression. Allowing for a 2 minute ascent, the figure would predict that this procedure would be safe if the DSRV (or DISUB) pressure is less than 24.5 psi (55 fswg or 2.7 ATA). This "decanting" procedure cannot be recommended for transfer from pressures greater than this, unless the circumstances permit no other alternative.

DSRV to MOSUB. As previously discussed, the forward compartment of the MOSUB can be used for decompression of the DISUB survivors, should the need exist. It is desirable to compress this compartment as little as possible, largely because of an abundance of equipment which is susceptible to damage by the large change in pressure (in hull integrity tests, where the compartment is exposed to 12 psi during final phases of submarine construction, much of the electronic equipment is removed (8)). Therefore, the optimal decompression would be a "step" decompression, where there is an immediate reduction in pressure on transferring from DSRV to MOSUB, followed by a long holding period (perhaps 24 hours). This would then be followed by a conventional saturation decompression schedule (see below). Current MOSUB procedures call for such a decompression, but only if the DISUB/DSRV pressure is greater than 4 ATA, because this is the maximum pressure safely attained by the forward compartment on US MOSUBs (2). The concept is not used for DSRV/DISUB pressures of 4 ATA or less. The safe magnitude of this initial step would depend on the saturation pressure, as suggested by several investigators in the past (9,10,11). However, little of this theory has been put to the test. Research is currently underway to address this question.

Some preliminary information is available. For example, to find the low end of the relationship, i.e., the air saturation depth from which one can decompress directly (no-stop) to the surface (1 ATA), almost 100 subjects have been exposed to pressures of 21.5 to 29.5 fswg (9.5-13.1 psi) for 48 hours, and decompressed directly to the surface (0 psi) (12). No cases of DCS were noted at the lesser pressure, but an increasing incidence occurred at the higher, to where almost 30% of the subjects sustained DCS on direct decompression from 13.1 psi. From these experiments, it can be predicted that about 10% of DSRV/DISUB occupants will have DCS symptoms (type I, or pain-only) on decompression from a prolonged exposure to 11 psi (1.75 ATA) air to normal atmospheric pressure (1 ATA). Greater pressures in the DSRV will require some degree of pressure in the MOSUB compartment. For example, British investigators have shown that a step from about 76 to 33 fswg (34 to 15 psi) is safely tolerated in small numbers of subjects (13). Future experiments at this laboratory will address the safe step from 5 ATA (132 fswg or 59 psi). By plotting these maximal safe steps versus the saturation pressure, and extrapolating in between (theory suggests that the relationship is approximately linear in the range 1-5 ATA), prediction of the maximal safe step for any point in the range of 26-132 fswg (11.5-59 psi) would be possible. This would be of obvious practical value in determining the required degree of MOSUB forward compartment compression in a pressurized DISUB scenario.

2. Decompression Schedules.

Atmosphere. The DISUB atmosphere will be air initially, but due to the survivor's metabolism, the oxygen level may be reduced by the time of rescue. If the DISUB pressurized oxygen source is used, it is conceivable, although unlikely, that the concentration of oxygen may be increased. In any case, the atmosphere will be some mixture of nitrogen and oxygen (nitrox). Since the U.S. Navy does not use air or nitrox for saturation diving, there are no official Navy schedules for decompression from a saturation length exposure. similarly, there are no well tested nitrox saturation decompression schedules in the civilian diving community. This situation is further complicated by the lack of a source of compressed nitrogen aboard the ASR or MOSUB. Air or helium-oxygen (heliox) is available in the former, and only air in the latter. The optimal atmosphere for decompression would be nitrogen-oxygen with an oxygen partial pressure around 0.40-0.50 ATA. This will probably allow recovery from pulmonary oxygen toxicity (see below), if present, and at the same time allow for more rapid decompression than a more physiologic partial pressure (0.20-0.30 ATA). Even though pure nitrogen is not carried by either the ASR or MOSUB, it is still possible to decompress the subjects in a reduced oxygen in nitrogen mixture, at least on an ASR . If, the DDC is initially compressed with air, the oxygen level could be "breathed down" to a pre-determined point (see below) by the survivors, and then maintained by the oxygen make-up system. Because of the small size of the DDC, and the number of survivors likely, this could be accomplished in a short period of time. For example, assuming an oxygen uptake of 1 liter/min/man, 30 men, DDC volume of 1000 cu ft and an atmospheric pressure of about 5 ATA, it would take about 8 hours to reduce the oxygen level to 0.50 ATA or below. Any selected oxygen partial pressure could then be maintained by current equipment on the ASR. Because of the much larger size of the MOSUB forward compartment, only a very small reduction in PiO_2 would occur, and therefore, the decompression would be essentially on air.

An alternative atmosphere for decompression on the ASR only, would be heliox. Much theory and some data on the concept of switching inert gases for decompression has been advanced over the past decade. For example, it has been shown in the laboratory, and later explained in theoretical terms, that a switch to a heliox atmosphere after saturation on air or nitrox may produce signs and symptoms of decompression sickness, without a change in hydrostatic pressure (14). This has been theorized to be due to the lower solubility and higher diffusivity of helium when compared to nitrogen, producing an overall inert gas supersaturation without a pressure reduction. In experiments at this laboratory it was shown that mild symptoms of decompression stress are produced on an isobaric switch to heliox from nitrox at 66 fswg (3 ATA), and more serious symptoms requiring treatment at 99 fswg (4 ATA) (15). Other studies have even shown venous bubble formation after such switching without a change in the ambient pressure (14). Therefore, the decompression of nitrox or air saturated DISUB survivors on helium-oxygen does not appear to hold promise with DISUB/DSRV internal pressure greater than 66 fswg equivalent, where potential benefit would be greatest.

Even another possible atmosphere for decompression would be a combination of the above - a trimix. It has been shown mathematically, but not experimentally, that if the helium is diluted somewhat by nitrogen, and the PiO_2 is about 0.50 ATA, an isobaric shift at up to 5 ATA would be tolerated without overt symptoms of DCS (1,16). This atmosphere could be easily achieved in the DDC by first compressing to 46 fswg on air, and then compressing the rest of the way on pure helium. The resultant atmosphere would have a PiO_2 of 0.50 ATA and varying percentages of helium and nitrogen, depending on the depth of compression (dictated by DISUB or DSRV internal pressure). Presumably, the DDC should remain at this pressure for at least 12-24 hours after the isobaric switch to be sure the time of peak supersaturation has passed, prior to initiating final decompression. A step type of decompression would probably not be safe under these conditions. As previously stated, this concept has not been tested, and should not be applied before documentation of safety in human subjects.

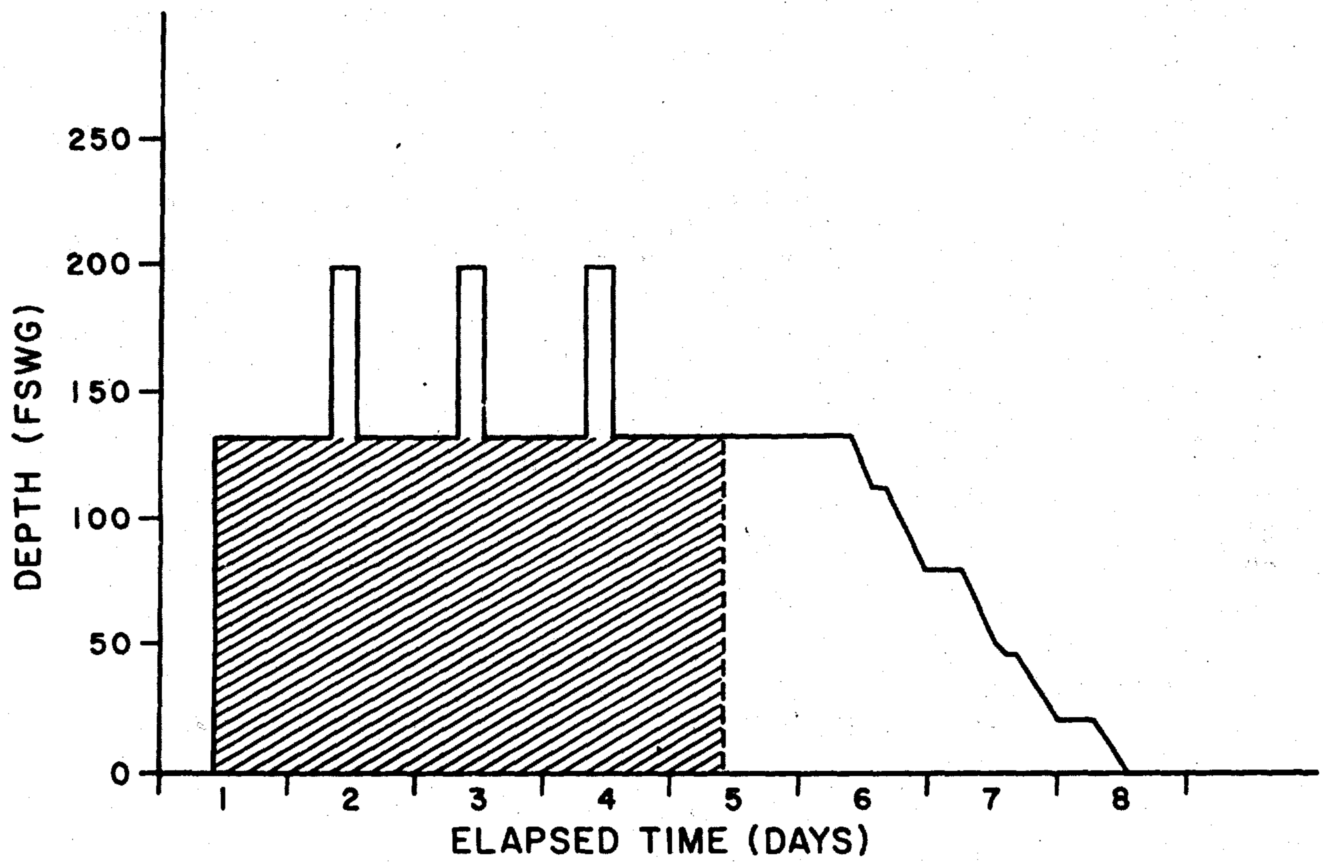
It would appear from the foregoing that a air or nitrox decompression is the simplest, and therefore, probably has the most merit. The complicating factor that remains is the degree of pre-existing pulmonary oxygen toxicity in the DISUB survivors, and this can be handled in the DDC by breathing down the oxygen, as discussed above. Since this does not appear to be possible in the MOSUB to any beneficial extent, alternate atmospheres for decompression would be desirable on the MOSUB. However, since the MOSUB does not carry helium, there appears to be no appreciable role for helium in the decompression of pressurized DISUB survivors. The only means by which to decompress <u>and</u> reduce the oxygen level in MOSUB would be a large ascending step, as discussed above.

Decompression Rates. Decompression from prolonged hyperbaric exposures must occur sufficiently slowly so that the inert gas tension in some "critical" tissue does not exceed the point of supersaturation, and produce a gas phase which may result in symptoms of DCS. This critical tissue is presumably the slowest to equilibrate because of perfusion and/or diffusion limitations. Therefore, saturation decompression rates are generally slow, and will vary depending on the inert gas gradient, and the inert gas species. A method of increasing the inert gas gradient for elimination is to elevate the inspired oxygen concentration; decompression schedules using an elevated oxygen level generally have more rapid ascent rates than normoxic schedules. Additionally, the inert gas species can affect ascent rate. Helium, for example, is much less soluble and more diffusible than nitrogen, resulting in more rapid uptake and elimination. Because of this, decompression schedules for heliox saturation exposures generally use more rapid ascent rates than those for equivalent air or nitrox exposures.

In the case under consideration here, the inert gas species will be nitrogen, with a variable concentration of oxygen. Unfortunately, most operational saturation diving, and therefore, decompression research, has been done with heliox mixtures, and not air or nitrox. As stated above, the U.S. Navy has no official decompression schedules for air or nitrox saturation dives. Those schedules which do exist have received little use due to the relative unpopularity of air or nitrox for saturation diving. Some recent studies have improved this situation somewhat, but confirmation awaits a large number of uses in the field.

Since the current U.S. Navy helium-oxygen saturation decompression schedule (Table 2) has had such a low incidence of DCS (<1%) from shallow heliox exposures (<150 fswg), attempts were made to see if it would suffice for shallow air or nitrox saturation exposures. Experiments at this laboratory showed that after a 5 ATA nitrox and air saturation-excursion exposure (see Fig.5), 3 of 12 subjects had symptoms of type I DCS (17), and the schedule required 54 hours. This high incidence was also observed at the Navy Experimental Diving Unit, with a 30 to 50% DCS rate from 60 fswg saturation exposures (18). Thus, this schedule appears to be unsatisfactory for safe <u>or</u> efficient decompression.

Other decompression schedules for saturation depths from 40 to 198 fswg air or nitrox have been formulated. Unfortunately, little uniformity in either formulation or testing has existed. Many of the published schedules are designed for use only for saturation at a specific depth, rather than the range of depths required here. Also, many involve oxygen breathing, and this is impossible in a submarine rescue scenario. Finally, and most importantly, the majority have received only cursory testing, making their usefulness essentially an unknown. This situation is unlikely to change substantially in the future. Air and nitrox saturation diving have still not gained the wide acceptance and use required for either the verification of theory or the justification of further research. Thus, potential air and nitrox saturation decompression schedules must be gleaned from the limited laboratory studies which have occurred over the past decade or so. The prerequisites for a suitable schedule are: a) simplicity and ease of



5. Pressurization and atmosphere profile for the AIRSAT 3 exposures in which the USN standard heliox saturation decompression schedule was used.

calculation, b) can be entered at any depth, c) requires no gases other than air and oxygen, d) yield a very low incidence of type II DCS, and e) be efficient enough to allow for DSRV turnaround time. Of these requisite features, only the last will be very difficult for the entire depth range of 20-132 fswg, as DSRV turnaround time is about 12 hours; only the shallowest exposures, with the fastest ascent rates can approach this time interval. It should be noted that a low incidence of type I DCS is not a prerequisite. Because of the gravity of the situation, a relatively large incidence of type I DCS may be acceptable, as few long-term adverse effects are anticipated from type I DCS. However, a decompression schedule which produces a large incidence of type I DCS may begin to produce a low incidence of more serious type II symptoms, and recompression treatment will be logistically difficult in a submarine rescue scenario.

The largest series of air and nitrox saturation decompression results has been reported from this laboratory recently (17). In this report, four different schedules were presented, each having been used for 12 to 24 subjects. The ascent rates for these schedules are shown in Table 2, and the overall incidence of DCS with each is shown in Table 3. The heliox schedule, above, was one of the schedules discussed. Also included was a schedule for saturation at 60 fswg, modified from a previous exposure at this laboratory (15). Although this schedule had an acceptable rate of type I and type II DCS, (2 of 23 and 0 of 23, respectively), its derivation is unclear, and it is limited to exposures of 60 fswg or shallower.

TABLE 2

SCHEDULES

1 DEPTHS*	RATE**	2 DEPTHS	RATE	3 DEPTHS	RATE	4 DEPTHS	RATE
60 - 45	10	75 - 70	15	132 - 100	12	132 - 50	24
45 - 20	15	70 - 60	17	100 - 50	15	50 - 40	26
20 - 5	33	60 - 50	19	50 - 0	20	40 - 30	30
5 - 0	36	50 - 40	22			30 - 20	36
		40 - 30	25			20 - 10	44
		30 - 20	30			10 - 0	58
		20 - 10	37				
		10 - 0	48				
TOTAL TIME 20:00		32:06**** 34:46		51:42***		65:08	

Notes:
* In feet sea water (fsw).
** In minutes per fsw.
*** Includes 16 hours of rest stops (see text).
**** Total time for schedule from 65 fsw.

A more useful decompression concept was used in the remaining two schedules in this report. Both of these schedules were derived from a simple relationship between the ascent rate and the PiO_2:

$$\text{Ascent rate} = K\ (PiO2) \qquad (1)$$

where the ascent rate in in fsw/hr and the PiO2 is in ATA. K is a constant which was empirically derived from an extensive review of all air and nitrox saturation decompressions in the literature. For air or nitrox exposures, this constant is between 5 and 6. It can, however, be easily changed to speed or slow the decompression depending on the requirements. In 42 man-decompressions (different subjects) from either 65 fswg (18 subjects), 75 fswg (6 subjects) or 132 fswg (18 subjects), there have only been two cases of DCS, and both were pain-only in character. Both cases occurred in the shallowest portions of the schedule (<10 fswg), and responded well to conventional forms of treatment. It is probable that both of these cases would have resolved in a day or two without any treatment, and would be unaccompanied by a significant long-term health effect. Doppler monitoring has shown that very low quantities of VGE are produced by the ascent rates calculated by this simple relationship. It has the advantage of being easy to remember and apply on the scene, from any saturation pressure or any inspired partial pressure of oxygen. It does not require the use of gases other than nitrogen and oxygen (or air), and it has had no serious DCS in 42 uses.

TABLE 3

SCHEDULE CHARACTERISTICS AND RESULTS

SCHEDULE	SAT DEPTH*	EXCURSIONS*	TOTAL DC TIME	# SUBJECTS	DCS SYMPTOMS
1(AIRSAT 1&2)	60	100 & 150	20:00	23	2 (8.7%)
2(SUREX)	65 & 75	0	32:06 & 34:46	24	1 (4.2%)
3(AIRSAT 3)	132	198	51:42	12	3 (25%)
4(AIRSAT 4)	132	NONE	65:08	18	1 (5.6%)

* - Units are feet sea water gauge(fswg)

A further possibility for saturation at less than 60 fswg (27 psig) would be to use the USN Treatment Table 7 (18) (will be in new revision of USN Diving Manual). Table 4 shows the ascent rates for this schedule, which is intended as a saturation treatment table for patients with illness refractory to more conventional forms of hyperbaric therapy. Presumably, this schedule would be used by starting with the ascent rates called for at whichever depth the DISUB survivors were located. In testing at the Experimental Diving Unit, it has produced 9 cases of type I DCS of 30 uses. Although this schedule is designed for saturation treatments, it could be easily used in pressurized submarine rescue for decompression on an ASR or a MOSUB.

TABLE 4

USN Standard Treatment Table 7
(decompression schedule)

DEPTH (fsw)	ASCENT RATE (fsw/hr)
60 - 40	3
40 - 20	2
20 - 0	1

Thus, sufficient data is currently available to allow selection of a suitable schedule for decompression of submarine survivors saturated with air or nitrox. The best candidates would appear to be the 5(PiO2) schedule for saturation exposures from 25 to 132 fswg, or the new USN Table 7 for exposures equal or shallow to 60 fswg. Although neither of these choices is efficient enough to allow for DSRV turnaround time, they provide safe, simple and easy to remember schedules. It should be remembered that DSRV turnaround time is only a consideration to decompression on an ASR, as the forward compartment on a MOSUB is sufficiently large to accommodate all the DISUB survivors.

C. Toxicity of respired gases.

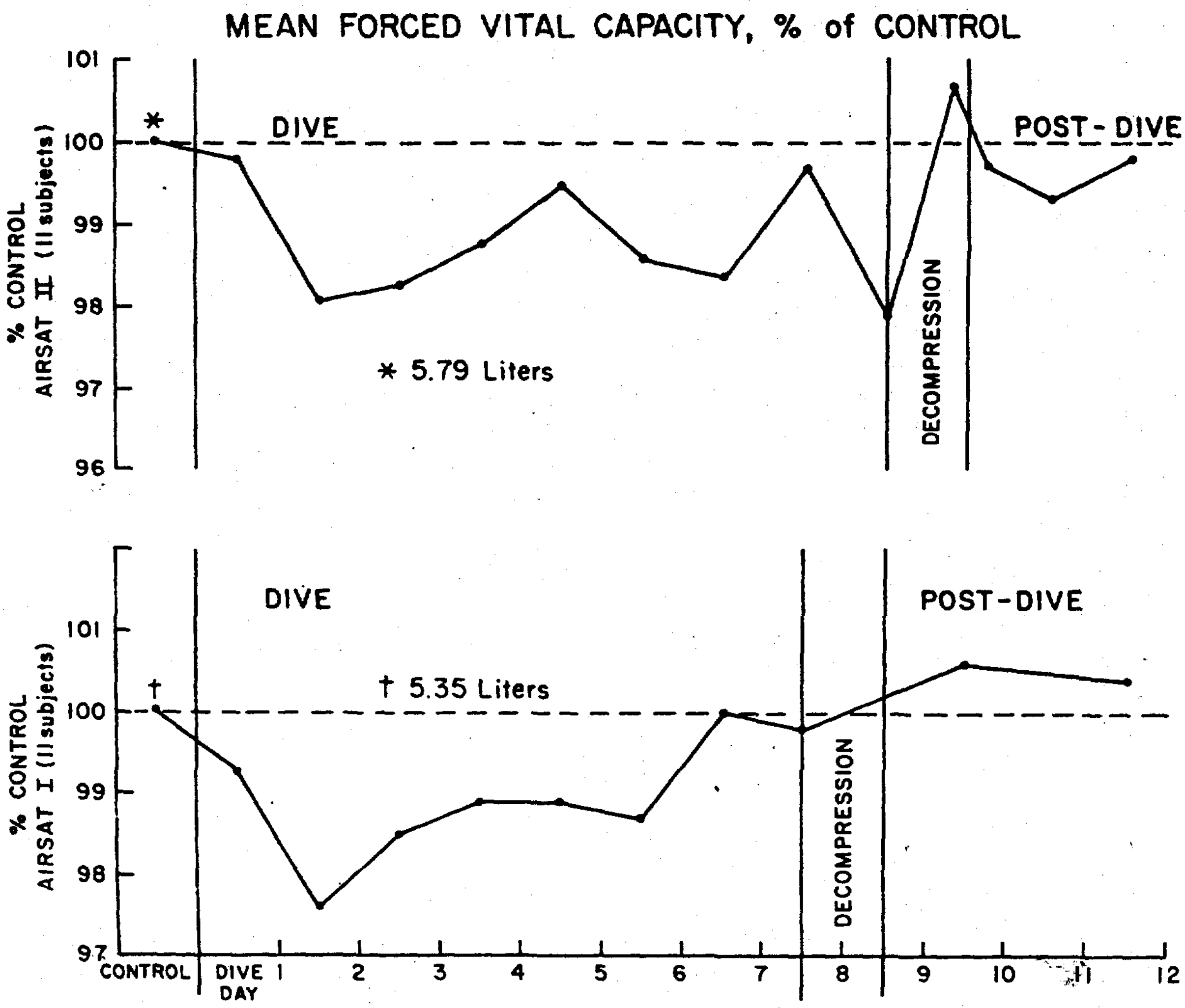
Compression of the submarine's atmosphere will result in an elevation in the partial pressure of all component gases. Since biological systems are affected by partial pressure or tension of a gas, as opposed to fraction, the effect of any component gases in the DISUB atmosphere will be amplified by compression. The atmosphere components can be divided into nitrogen, oxygen, carbon dioxide and contaminates.

1. Nitrogen.

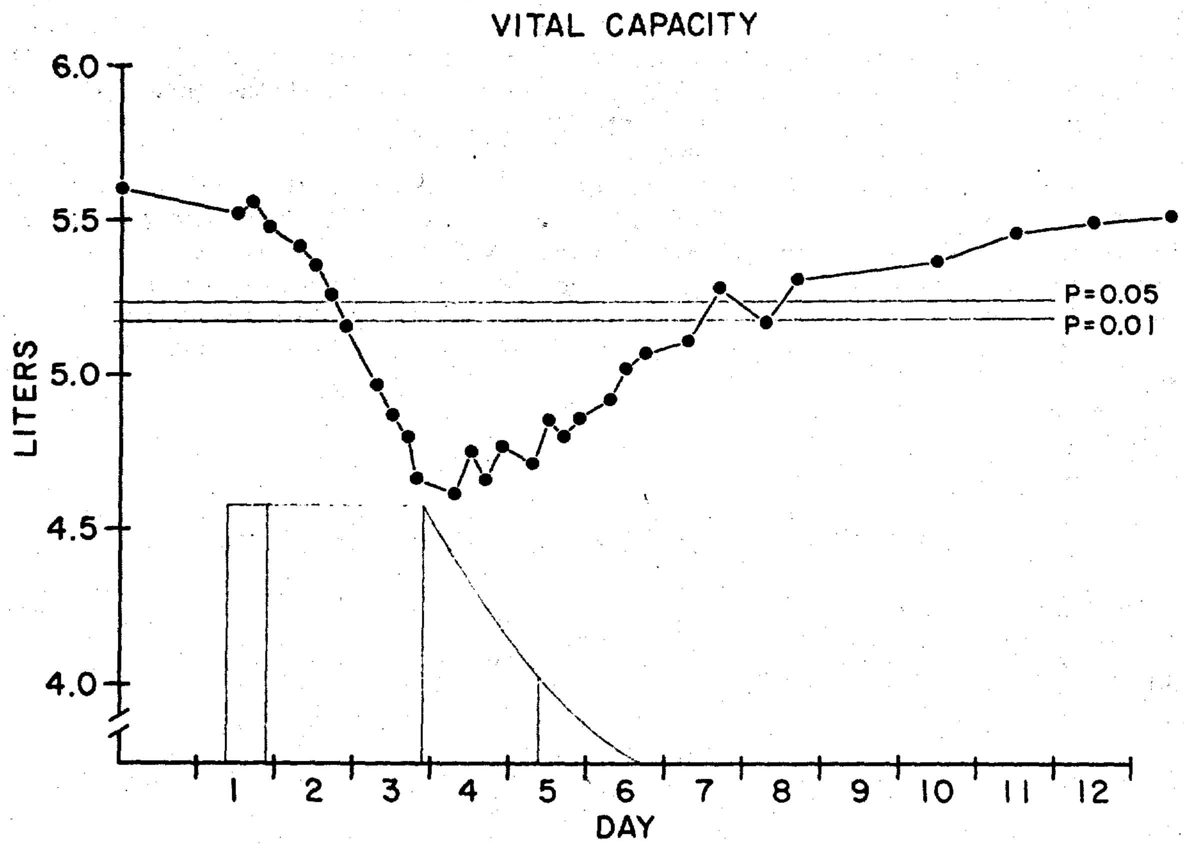
Nitrogen causes narcosis in a dose-dependent fashion similar to nitrous oxide. Some data exists to show that a relative performance decrement is present even when breathing air at 1 ATA, compared with 80% helium 20% oxygen. The narcosis increases as the pressure increases to where debilitation occurs above about 8 ATA (9.3 ATA nitrogen) when breathing air. Nitrogen narcosis is relatively mild at 5 ATA, and although decrements in performance can be measured in a laboratory setting (19), it is unlikely that this factor would be a significant factor limiting either survival or performance of the DISUB crew in a pressurized rescue. On the other hand, the DSRV crew members exposed to pressure (mid-sphere operators) are required to perform many intricate procedures in completing a rescue, and therefore can least afford an atmosphere-imposed performance decrement. Since there is some evidence which suggests adaptation to the narcotic effect of hyperbaric nitrogen occurs with repetitive exposures (20), it may be advantageous to do a portion of their training under pressure to familiarize them with the narcotic effects of hyperbaric nitrogen (most DSRV operators are submariners, not divers, and are therefore unaccustomed to these effects).

2. Oxygen.

Although oxygen is essential to support human life, it is also highly toxic when present in more than usual amounts. Breathing 100% oxygen at 1 ATA will result in a progressive and eventually fatal lung poisoning called pulmonary oxygen toxicity (POT). When air is breathed under pressure, the partial pressure (dose) of oxygen is elevated although the fraction, or percentage, is not. An inspired oxygen partial pressure (PiO_2) of about 0.60 ATA will cause pulmonary symptoms in most humans in less than 24 hours, and this is achieved by breathing air at only 61 fswg. This was demonstrated in earlier experiments at this laboratory (AIRSAT 1 & 2), where subjects were exposed to air at 60 fswg (27 psig) for up to a week (21). Mild symptoms of cough and chest tightness began at about 24 hours, and small but definite drops in vital capacity were noted (Fig.6). Instead of becoming progressively worse, however, the symptoms and signs improved over the next two days without a change in PiO_2 or pressure. This is believed to indicate that a PiO_2 of 0.59 ATA is very close to a toxic "threshold". At greater depths or pressures, POT is progressive. At 5 ATA (132 fswg - 59 psig), the PiO_2 is 1.05 ATA, and this partial pressure has been shown to be fatal in animals in prolonged exposures (> 72 hours). Clearly, this is pertinent to the pressurized rescue scenario, as the potential pressures and time delays could easily result in toxicity of sufficient severity to limit survival.



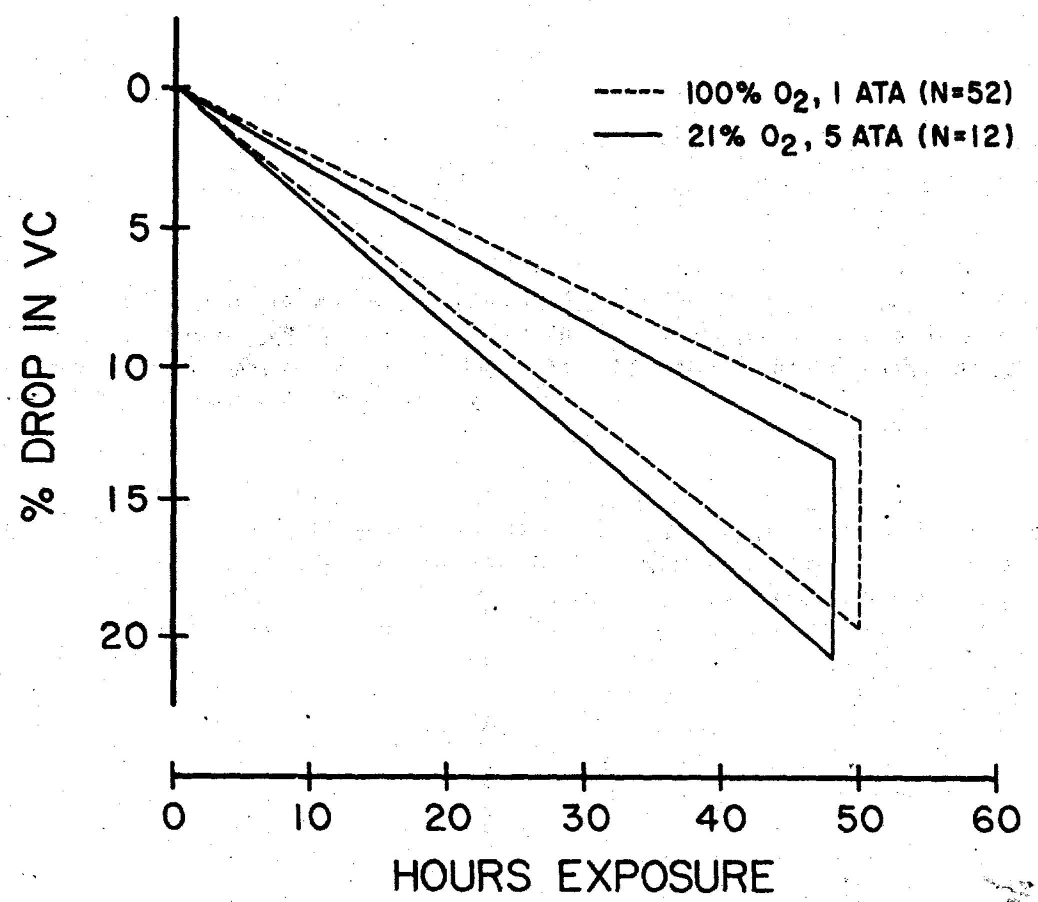
6. Mean vital capacity from AIRSAT 1 (lower graph) and AIRSAT 2 (upper). Note the early drop of about 2% in both groups, which then recovered or stabilized. The initial drop was accompanied by mild symptomatology consistent with pulmonary oxygen toxicity.



7. Mean vital capacity of 12 subjects on exposure to 48 hrs of 5 ATA. The inset dive profile shows the timing of these events. The nadir was reached about 12 hours <u>after</u> termination of the 5 ATA air exposure, and represented about an 18% drop from their pre-exposure values. Recovery to baseline required another 5 to 7 days.

The exposure duration necessary to produce significant toxicity can be, to some extent, gleaned from the clinical literature where much data is available for human exposures to normobaric 100% oxygen (PiO_2 = 1.0). Continuous exposures of up to 72 and even 110 hours have been reported in the literature in healthy subjects. Although significant signs and symptoms of POT were produced, complete recovery occurred with reduction of the oxygen level to normal. There is some question however, whether or not breathing pure oxygen at 1 ATA is tolerated the same as diluted oxygen at the same partial pressure (air at about 5 ATA). Animal work has demonstrated a protective effect of the nitrogen diluent, in a dose dependent fashion (22). The protection, however, is limited to the rate of progression of the toxicity; the ultimate outcome (death) remains the same, at least at a PiO_2 of 1 ATA. Human data on this point does not exist. Until recently, there have been little data to even show that POT occurs in humans exposed to hyperbaric air. Experiments were performed at this laboratory in an attempt to define the onset and rate of progression of POT in humans exposed to 5 ATA air. Twelve healthy subjects were exposed to 5 ATA air in a dry hyperbaric chamber for 48 hours, and gas exchange and pulmonary function were measured as indices of POT. Significant signs and symptoms of POT were detected in all subjects, with substernal pain, cough, dyspnea, anorexia, nausea and vomiting being the predominate symptoms. Large drops in the vital capacity were noted as shown in Fig. 7. For comparison, 6 subjects were exposed to 5 ATA nitrox (PiO_2 = 0.30 ATA), and neither symptoms nor vital capacity changes were detected. The experimental group showed a linear fall in the vital capacity from the beginning to the end of the exposure. The mean nadir (18% decrement from baseline), was reached about 12 hours into the recovery.

We compared the rate of VC decrement seen in these studies with that obtained from raw data excerpted from several 1 ATA 100% oxygen studies reported in the literature (23-29). The 95% confidence interval around the slope of a regression line describing each data set shows almost complete overlap (Fig.8). In other words, there does not appear to be any significant effect of the inert gas diluent at this stage of the toxicity (30). It is entirely possible that a protective effect would be observed much later in the poisoning. In any case, the toxicity of the DISUB environment can be reliably estimated from this work as well as what is reported for normobaric 100% oxygen studies. Exposures of 48 hours will be tolerated safely, with complete recovery, in the vast majority of survivors, but a small percentage will have incapacitating symptoms.



8. Comparison of the <u>rate</u> of VC decrement observed in these 5 ATA air exposures (12 subjects) with that obtained from the literature (54 subjects) for 100% normobaric oxygen. The 95% confidence intervals for the slope were obtained by least squares regression analysis of the data in both cases. The almost complete overlap of these confidence intervals (zones) indicate that no significant difference exists between the data sets. Therefore, 5 ATA air is tolerated the same as 100% oxygen at 1 ATA, and no effect of the 4 ATA nitrogen is apparent.

Significantly longer exposures will be associated with an increasing morbidity and mortality due to this single factor, and the subsequent handling and recovery of these survivors will be significantly complicated.

As previously mentioned, an atmosphere with an elevated oxygen partial pressure is desirable for decompression, either in the MOSUB or on the ASR. It should not, however, be so high that recovery from POT is impossible, or that the toxicity progresses further. This becomes an important factor if the breathing media is air, and the pressures greater than 4 ATA. Although the step decompression could reduce the PiO_2 immediately, as previously noted, it could still be well above normal. This is more of a problem with the MOSUB, because of the inability to breathe down the oxygen due to the large size of the forward compartment. Until recently, however, there has been no data available in the literature to suggest what a safe PiO_2 for recovery might be. Some animal data suggests that recovery from acute lung damage is possible at a PiO_2 of 0.50 ATA (31). Similarly, the aforementioned 5 ATA air studies have shown that recovery from acute POT in most subjects is possible in a 0.50 ATA PiO_2. It is important to note, however, that a few subjects continued to deteriorate (more slowly than at 1.05 ATA) until the PiO_2 fell below 0.50 ATA. Therefore, a PiO_2 of about 0.50 ATA should be considered maximal for decompression of survivors who have significant symptoms of POT. If no symptoms are present, a higher PiO_2 may be tolerated, possibly 0.65-0.75 ATA, as it is unlikely that serious symptoms of POT will be produced during the decompression.

Although full recovery, and a lack of long term effects has been demonstrated for the subjects in the 48 hour 5 ATA air study, longer exposures may produce more significant pulmonary damage, and therefore the chance of long term effects (i.e., pulmonary fibrosis) is increased. The acute treatment for POT will probably require little other than reduction of the PiO_2. It may not be best to reduce it to normal levels, however, because if a significant gas exchange defect should exist as a result of the POT, an atmosphere with an elevated PiO_2 may be necessary for adequate oxygenation until sufficient recovery occurs to reverse the defect (weaning).

3. Carbon dioxide.

Elevation in atmospheric pressure will increase the partial pressure of CO_2 in an analogous manner as O_2. Thus, the biological effect of 2% CO_2 at 5 ATA will be roughly equivalent to 10% CO_2. Thus, removal systems must be efficient enough to keep the CO_2 well below 2%. However, the systems for emergency CO_2 removal on US submarines are primitive at best. The rescue protocol calls for spreading the absorbant (lithium hydroxide) over bunks, or other horizontal surfaces. A more effective approach would be the use of manual bellows, such as those being investigated by the Royal Navy. In simulated DISUB conditions, these foot operated bellows maintained the CO_2 at 2% or below (32). It is likely that this sort of device will perform equally well under pressure, but this remains to be shown.

Aside from the well known effects of acute hypercarbia, elevations in atmospheric CO_2 may affect both the progression of POT, and the susceptibility to DCS, presumably for the worse in both cases. Only speculation is possible, as little or no data concerning these points exists. One study in rats has shown that at a PiO_2 of 1 ATA, elevated CO_2 has no effect on the characteristics of POT (33). Preliminary investigations into the effect of elevated CO_2 on decompression outcome from shallow air saturation exposures are currently being conducted by UK laboratories, and at this point, it appears that there is no effect of 2% CO_2 on direct decompression from shallow nitrox saturation exposures. More work will be needed to clarify these issues.

4. Contaminates.

Trauma to a submarine has a high likelihood of producing atmosphere contamination. Products of combustion, battery gases, etc., may all be present in the DISUB. These contaminates are generally highly toxic at 1 ATA, and thus can be expected to be more of a problem under pressure. Therefore, significant contamination in a pressurized DISUB will likely result in the crew's demise long before rescue can occur. Under these circumstances, individual escape may offer a greater chance of survival.

VI. CONCLUSIONS

Any event resulting in the sinking of a submarine has a high probability of causing compression of the submarine's atmosphere. Pressurization of the DISUB significantly complicates the rescue process. Anticipated medical problems caused by DISUB pressurization include decompression sickness and inspired gas toxicity, both of which could reduce the probability of a successful rescue mission. Decompression schedules and transfer procedures for air and nitrox saturation exposures have been formulated and verified. The character and progression of oxygen toxicity in hyperbaric air has been described, and recovery at an elevated oxygen level documented. Although a few problems which require further investigation still remain, sufficient physiologic information now exists to allow authorization of pressurized rescue, so that appropriate training exercises can occur. This has the potential of identifying further procedural and hardware problems which, when corrected, would improve the capability of present submarine rescue systems to perform their primary mission under a variety of circumstances.

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Any event that sinks a submarine is likely to cause compression of the atmosphere because of flooding, salvage air pressurization, high pressure air leaks and exhaust from the open circuit emergency breathing system. The anticipated degree of pressure is impossible to define, but rescue systems (Deep Submergence Rescue Vehicle - DSRV) are limited to a maximum of 5 atmospheres absolute (ATA). The disabled submarine's crew is likely to be exposed for longer than 48 hours. Pressurization significantly complicates the rescue process, since means of

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pressure equalization and pressurized transfer are required. Medical problems associated with pressurization of the submarine's atmosphere include decompression sickness and toxicity of the inspired gases. Decompression schemes must consider the hardware and procedural constraints involved in submarine rescue. For example, the optimal decompression profile is substantially different depending on whether the DSRV is discharging the survivors to a surface craft (ASR) or another submarine (MOSUB). Decompression schemes, transfer procedures and ascent rates for air or nitrogen-oxygen (nitrox) saturation exposures have been formulated and verified in the laboratory, and are presented in this report. Oxygen toxicity is a potential complication if the pressure is greater than 26 psig due to the elevated partial pressure of oxygen in hyperbaric air. Data is presented, which describes the onset, character and progression of pulmonary oxygen toxicity in hyperbaric air. The toxicity of other atmospheric gases is discussed as well. Pressurized submarine rescue is currently an unauthorized procedure due to the lack of medical knowledge in this area. This report suggests that sufficient physiologic information now exists to allow the authorization of pressurized rescue so that appropriate training exercises can occur. This has the potential of identifying further procedural and hardware problems which, when corrected, would improve the capability of present submarine rescue systems to perform their primary mission under a variety of circumstances.